Channel Group	Allotments	Separation (border to border) (miles)
9	Aitkin, Clearwater	68
10	-	-
11	St. Cloud, Ottertail	60
12	Cass, Wilkin	71
13	-	-
14	-	-
15	-	-
16	-	-

Individual Channels		
79	-	-
80	-	-
81	Benton, Burnett, WI	43
88	Blue Earth, Olmsted	55
89	Pine, Stearns	50
89	Stearns, Nicollet	57
89	Nicollet, Dodge	47
90	Renville, Waseca	45
90	Waseca, Wabasha	43
90	Wabasha, Barron, WI	53

Attachment 15

Attachment 15

Wideband Data Channels
150 KHz Contiguous Groups
July 22, 2004

Supergroup	Group	Channels
B	1	31, 32, 33
A	9	34, 35, 36
B	2	40, 41, 42
A	10	43, 44, 45
B	3	49, 50, 51
A	11	52, 53, 54
B	4	55, 56, 57
A	12	58, 59, 60
B	5	61, 62, 63
A	13	64, 65, 66
B	6	67, 68, 69
A	14	70, 71, 72
B	7	76, 77, 78
A	15	79, 80, 81
B	8	85, 86, 87
A	16	88, 89, 90

Attachment 16

Attachment 16

Vehicle Infrastructure Integration (VII): A Minnesota Perspective

June 30, 2004

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Objective

Vehicle-Infrastructure Integration (VII) has received significant national attention from the US DOT, AASHTO, state Departments of Transportation, and automobile manufacturers. Most of this attention has been focused on the deployment of the Dedicated Short Range Communication (DSRC) system. The FCC has issued final rules regarding DSRC (on December 17, 2003), allocating 75MHZ of bandwidth in the 5.9GHz band to be used primarily for safety applications by allowing vehicles to communicate with the infrastructure, allowing the infrastructure to communicate with vehicles, and allowing vehicles to communicate with other vehicles. As presently written, the maximum allowable range is 300m for normal communications to/from vehicles and an extended range of 1000m for emergency response vehicles. The primary enabling technology for VII is wireless communication. However, VII is more than wireless communication and wireless communication is more than DSRC.

The objectives of this document are fourfold. The first objective is to illustrate why VII is needed from a safety perspective (primarily fatal traffic crashes), and what its role in crash prevention should be. The second objective is to identify the dominant use cases for VII from the safety perspective. The third objective is to identify the role of wireless communication in general, and DSRC in particular. The fourth objective is to discuss architectures that support the timely deployment of VII for safety applications.

Through the course of this document, Minnesota's crash database (Crash Facts) is used to identify the early candidate use cases for Minnesota. Minnesota statistics clearly point to rural lane departure crashes and rural intersection crashes. However, national statistics show that the specific references to Minnesota crashes contained herein will reliably extrapolate to a majority of the other states in the US. It is worth noting that more than three quarters of the states have significantly more rural road fatalities than urban fatalities. Not coincidently, Minnesota has already focused its attention on these rural crashes for a number of years with systems that utilize VII-type strategies.

Introduction

The title of the 2003 Minnesota DOT Strategic Plan, "Helping Minnesotans Travel Safer, Smarter, and More Efficiently," sets the stage for the role VII should play in the improvement in the Minnesota road transportation network. As is indicated in the title, Safety is the priority. Smarter driver are safer drivers, and an efficient network is a safe network.

Fewer crashes, few injuries, and fewer deaths are all representative of a safer transportation network. Within this context, where should priorities be placed? Mn/DOT has initiated a "Toward Zero Deaths" program, the focus of which is to lower the fatality rate on Minnesota roads. This goal is in alignment with the US DOT goals. Transportation Secretary Norman Mineta has established a goal to reduce the highway fatality rate to not more than 1.0 per 100 million vehicle miles traveled by 2008 from 1.7 per 100 million vehicle miles traveled in 1996.

The descriptions Safer, Smarter, and Efficiently should be examined from the perspective of VII to determine the role VII will play in helping Minnesota achieve its transportation goals.

"Safer" should encompass both personal safety and security. A focus on personal/passenger safety in terms of improved vehicles has led to innovations in air bags, structural integrity, ABS, and other vehicle-centric technologies and techniques. The aftermath of 9/11 has illustrated that the security of the transportation network directly affects citizens' personal safety. Improvements in personal safety based on vehicle-centric technologies have reached a plateau; future improvements in crash worthiness, structural integrity, and vehicle handling and dynamics are likely to be marginal. The next series of improvements will need to come from improving the road transportation *system* and the interaction between the vehicle and the infrastructure.

"Smarter" encompasses the intuitive transfer of appropriate information to a driver when it is needed. Although some of this information can be accessed by a driver before a trip, the information a driver needs comes predominately from the infrastructure during the trip. This includes traffic information, weather information, road construction, road conditions, etc. This information is presently passed to the driver via wireless communications (AM/FM and satellite radios, cell phones, 511) or directly by the infrastructure using Variable Message Signs.

Beyond the benefits of information that the driver has requested, "smarter" will also encompass the delivery of information a driver may not request. Speeding and running stop signs/red lights are two examples where providing information which has not been requested by a driver may improve safety. In the future, "smarter" will also include the transfer of information to the vehicle's control system so that it can take advantage of such information in order to respond to situations when the driver's response characteristics are inadequate to avoid a collision.

"Efficiently" **reflects the continually increasing congestion on Minnesota's roads. As more and more of Minnesota's roads reach design capacity, the system throughput saturates (in the best scenario) or actually decreases due to a disproportionately high incidence of crashes, which cause localized congestion or complete standstills while support and emergency services are dispatched. By making the transportation system *safer*, the frequency of congestion causing crashes is likely to decrease. A lower frequency of traffic incidents is likely to lead to improved traffic flow, and thereby higher transportation network efficiency.**

Since rights-of-way have been nearly completely consumed in urban areas, and because of the increased cost of right of way acquisition and construction in rural areas, the traditional approach of adding capacity by adding lanes is unlikely to continue for long. Therefore, significant increases in capacity will only come to be because of advancements in collision avoidance technologies and improved traffic management techniques. Both of these methods require significant cooperation between vehicles and the adjacent infrastructure.

In what follows, an approach to VII is presented, and contrasted with other published views on VII. Our definition of VII is likely the broadest, but it offers the greatest set of possible solutions to the problems faced in Minnesota as well as for the entire the US.

Following the definition of VII, the Minnesota Crash Facts and the Toward Zero Deaths initiative are used to determine which scenarios contribute to fatal crashes in Minnesota. Once these scenarios are identified, the role of VII as a means to mitigate these fatal crashes will be explored, and recommendations regarding how VII deployment should be prioritized will be given.

What is VII? The VII Toolbox

Improvements in traffic safety, intelligence, and efficiency will rely on new paradigms, with the fundamental paradigm being the treatment of the roads and vehicles as elements of a *system* instead of entities on their own. The unifying catalyst of this systemic approach to transportation is the emergence of wireless communication technology which enables the transmission of information

- From vehicles to the infrastructure
- From the infrastructure to vehicles
- From vehicle to vehicle.

However, communication is only the catalyst. A number of other components are needed to produce a viable system capable of producing improvements in safety, security, and efficiency.

To some, VII is simply wireless communication (or the communication "pipeline") for which vehicle and infrastructure components pass information back and forth. Moreover, because the FCC has dedicated 75MHz of bandwidth in the 5.9GHz as Dedicated Short Range Communication (DSRC) for Intelligent Vehicle applications, DSRC is considered by some to be VII, and *vice versa.*

However, views of VII that are broader than that of the communication link have also been presented. At the 2004 ITS America meeting in San Antonio, Dave Acton of General Motors presented his 7 components of VII. These 7 components are:

1. Maps (higher accuracy than what is commercially available)
2. Vehicle strategy (includes Human Machine Interfaces (HMI), links to handhelds)
3. Pipelines (need multiple communication pipelines)
4. Back office strategy (includes data structure, data sharing, data fusion)
5. Content & application (where the value gets created, where the revenue gets captured)
6. Data policy
7. GPS (high accuracy, capability to match accuracy of maps)

Although the Dave Acton view is broader than that of solely a wireless communication link, this view remains too narrow. In our view, VII is any transportation system which uses the following elements to improve the safety and mobility of the transportation network. The toolbox from which VII systems are built include the following components:

1. Communications – both wired and wireless
    a. DGPS corrections (continuous signals, at least 4800 kbaud) – high accuracy DGPS is needed for lane departure prevention systems
    b. Traveler information (road conditions, traffic conditions, updates to digital maps, etc.)
    c. Automatic crash notification, E-911 services
    d. In-vehicle collision avoidance warnings (i.e., at intersections)
    e. Short range, low power transponders (HOT lanes, FAST lanes, etc.)
    f. Digital cell phone based communications
    g. AM/FM sidebands and satellite radio
    h. 700 and 800 MHz public communication bands
    i. New bands allocated by the FCC (e.g. DSRC 802.11p) for vehicle-to-vehicle and vehicle-to-infrastructure communications
2. Sensors
    a. GPS for low accuracy applications – E911 Dispatch, Automatic Vehicle Locations, etc.
    b. DGPS for high accuracy applications – lane departure warnings, vision enhancement systems, etc.

    c. Radar, laser ranging and imaging systems for surveillance, intersection decision support, etc.
    d. R/WIS (infrastructure based)
    e. Road-tire friction and other road conditions that affect driver safety (vehicle based)
    f. Traffic counters
    g. Enhanced cameras for monitoring traffic
3. Databases
    a. Geospatial databases (i.e., digital maps, including locations of lane and road boundaries, traffic control devices, e.g. stop signs, signals, etc., road attributes, e.g. speed limits, and other relevant detail)
    b. Traffic data (flow rates, traffic counts, origin-destination info)
    c. Crash data (updated in real time)
    d. Revenue (for HOT, FAST Lanes, commercial vehicles, etc).
    e. HazMat Tracking and other commercial vehicle data
4. Data processors
    a. On-board the vehicle for lane departures, collision avoidance, etc.
    b. Local infrastructure based (intersection decisions support, intersection crash warnings, etc.)
    c. Central servers for traffic management, emergency response, etc.
5. Actuators
    a. Traffic signals
    b. Ramp meters
    c. Traffic incident and emergency response (ambulance, fire) teams
    d. Police/state patrol (incident response)
    e. Variable message signs
    f. In-vehicle signing
    g. Road maintenance crews
6. Human interfaces
    a. Lane departure warnings
    b. Intersection collision warnings
    c. Traveler information
    d. Human-machine communications, including voice, haptic, visual, etc.
    e. Location/task based decision making

The Acton model can be created from the Minnesota toolbox, but not *vice-versa.* Under the Acton model, the Minnesota R/WIS system would not be considered as an element of a VII system. However, R/WIS plays an important role in maintenance and traffic control operations, and with the proper communication infrastructure in place, could be used to provide travelers with in-vehicle, real-time weather information.

Given this definition of VII, the next logical step is to determine how VII fits into the Minnesota's transportation goals, where reduction in fatalities is its highest priority.

Crashes in Minnesota

Highways in general. Given the emphasis on safety in the Mn/DOT Strategic plan and the Minnesota cooperative initiative 'Toward Zero Deaths' (http://www.tzd.state.mn.us), the logical starting point to determine VII priorities is the Minnesota Crash Facts 2002 document (http://www.dps.state.mn.us/OTS/crashdata/crash_facts.asp). In general, the data shows that rural crashes and urban crashes are quite disparate. Just as crash statistics are different for rural and urban areas, technical issues with communication and sensors systems are divergent as well. First, we will discuss the characteristics of rural and urban crashes and then we will describe rural and urban technical issues in the subsequent section.

Table 1 shows that 67% of the fatal crashes occurred in areas with a population of less than 1000, or equivalently, on roads adjacent to fields, forests, lakes, or other open areas. Table 1 also indicates that 64% of all crashes occur in areas with populations of 10,000 or greater. A clear dichotomy is present[1].

Table 1. 2002 Crashes by Population of Area (from 2002 Minnesota Crash Facts)

Population of City or Township	Fatal Crashes	Personal Injury Crashes	Property Damage Crashes	Total Crashes	Killed	Injured
100,000 & Over	25	5,427	15,727	21,179	27	7,366
50,000 - 99,999	28	4,298	8,714	13,040	30	6,055
25,000 - 49,999	42	3,410	8,173	11,625	46	4,848
10,000 - 24,999	41	4,131	10,142	14,314	43	5,968
5,000 - 9,999	29	1,724	4,147	5,900	32	2,507
2,500 - 4,999	24	1,001	2,797	3,822	28	1,478
1,000 - 2,499	6	487	1,457	1,950	6	708
Under 1,000	395	7,662	15,082	23,139	445	11,747
Total	**590**	**28,140**	**66,239**	**94,969**	**657**	**40,677**

Table 2 below shows crash statistics based on the crash diagrams from the 2002 Crash Facts. This table shows that lane departure fatalities (as indicated by the dark gray highlights) represent 54% of all fatalities in the state, and that intersection crash fatalities represent 22 % of all fatalities in the state (as indicated by the light gray shading).

Table 2. Crashes by Diagram (from 2002 Minnesota Crash Facts)

Diagram	Fatal Crashes	Personal Injury Crashes	Property Damage Crashes	Total Crashes	Killed	Injured
Rear End	20	7,244	14,942	22,206	21	10,575
Sideswipe Passing	8	743	4,962	5,713	8	978
Left Turn -- Oncoming Traffic	11	1,749	2,920	4,680	11	2,697
Ran Off Road - Left	102	2,156	3,072	5,330	112	2,826
Right Angle	115	6,398	9,808	16,321	133	10,124
Right Turn -- Cross Street Traffic	1	134	380	515	1	180
Ran Off Road - Right	129	2,818	4,445	7,392	135	3,720
Head On	86	1,102	1,474	2,662	106	1,956
Sideswipe Opposing	15	366	925	1,306	15	552
Other / Unknown / Incomplete	103	5,430	23,311	28,844	115	7,069
Total	**590**	**28,140**	**66,239**	**94,969**	**657**	**40,677**

Table 3 below provides crash and fatality rates for the roadway/jurisdictions found in Minnesota. Clearly, per mile traveled, the Interstate system has by far the lowest crash and fatality rates. However, Trunk Highways and County roads have fatality rates

[1] The official definition of rural vs. urban uses a local population of 5,000 as the defining boundary.

approximately three times higher than rural interstates. This is a significant jump, and can likely be explained by the fact that the US and Minnesota Trunk Highways comprise approximately 9% of the total state lane miles, yet carry approximately 61% of the vehicle miles traveled in the state.[2] High traffic volumes combined with high average speeds lead to both higher crash and higher fatality rates.

Table 3. Roadway Segment Crash and Fatality Rates By Jurisdictional Class (From Traffic Safety Fundamentals, Minnesota Department of Transportation Office of Traffic Engineering, April 2001)

Roadway / Jurisdictional Classification	Miles	Crashes	Fatalities	Crash Rate[3]	Fatality Rate[4]
Interstate total	914	11149	61	1.0	0.5
Trunk Highway	11,012	2828,211	270	1.4	1.4
County Roads/CSAH	45,356	2626,631	217	2.2	1.8
City, MSAS & Municipal	18,259	2727,701	45	3.8[5]	0.6
Other (Township, etc.)	56,109	33,121	33	2.9	3.1[6]
Total	131,650	9696,813	626	1.9	1.2

Table 4 expands on Table 3 by providing a further breakdown of urban and rural crashes. In terms of fatal crashes, rural roads have crash frequencies approximately 3 times greater than those in urban areas. Table 3, however, does not break down lane miles between urban and rural areas, making it difficult to break these numbers down in terms of crashes and fatalities per lane mile. (Per mile numbers are important when considering deployment of sensors and communication equipment which operate over a limited range.

Table 4. 2002 Crashes by type of Highway (from 2002 Minnesota Crash Facts)

Type of Roadway	Fatal Crashes	Personal Injury Crashes	Property Damage Crashes	Total Crashes	Killed	Injured
Urban						
Interstate	31	1,975	6,570	8,576	34	2,708
US Trunk Highway	21	1,614	3,717	5,352	23	2,355
MN Trunk Highway	31	3,012	6,705	9,748	35	4,409
County State Aid Highway	45	5,674	11,986	17,705	47	8,155
County Road	1	208	334	543	1	295
Local Street	36	6,507	17,591	24,134	38	8,822

[2] See http://www.dot.state.mn.us/information/overview.html.
[3] Per Million Vehicle Miles
[4] Per 100 Million Vehicle Miles
[5] Higher crash rates are expected in urban areas because of high traffic densities. Because of lower speeds, the fatality rate is quite low.
[6] High fatality rates in rural areas are typically due to long response time for emergency personnel, and the distance to a trauma center. This makes a case for automated crash notification and expanded wireless E-911 services throughout the rural areas in the state.

Total	**165**	**18,990**	**46,903**	**66,058**	**178**	**26,744**
Rural						
Interstate	30	646	1,821	2,497	38	941
US Trunk Highway	72	1,577	3,254	4,903	80	2,578
MN Trunk Highway	102	2,157	4,578	6,837	119	3,437
County State Aid Highway	165	2,879	5,125	8,169	184	4,291
County Road	27	480	833	1,340	28	721
Township Road	23	778	1,176	1,977	24	1,147
Local Street	2	438	1,719	2,159	2	579
Other Road	4	195	830	1,029	4	239
Total	**425**	**9,150**	**19,336**	**28,911**	**479**	**13,933**

Intersections in particular. The 1998 AASHTO Strategic Highway Safety Plan indicates that about one in every four fatal crashes occurs at or near an intersection, one-third of which are signalized. This number is substantiated in Table 2, where approximately 22% of all fatal crashes in Minnesota are reported as right angle crashes.

There were 164 fatal crashes at rural intersections in Minnesota in 2002. As shown in Figure 1, 60% of all fatal crashes at rural intersections in Minnesota occurred at Thru-Stop intersections. Notably, the ratio of drivers who stopped, looked, and made a poor decision regarding gaps, to those who ran the stop sign is 2:1. The breakdown of Thru-STOP contributing factors is shown in Figure 2.

It is important to note that in Minnesota, rural SIGNALIZED intersection crash fatalities represent only 10% of the total rural intersection crash fatalities. We hypothesize that this trend is representative of the intersection crash fatality statistics in other states.

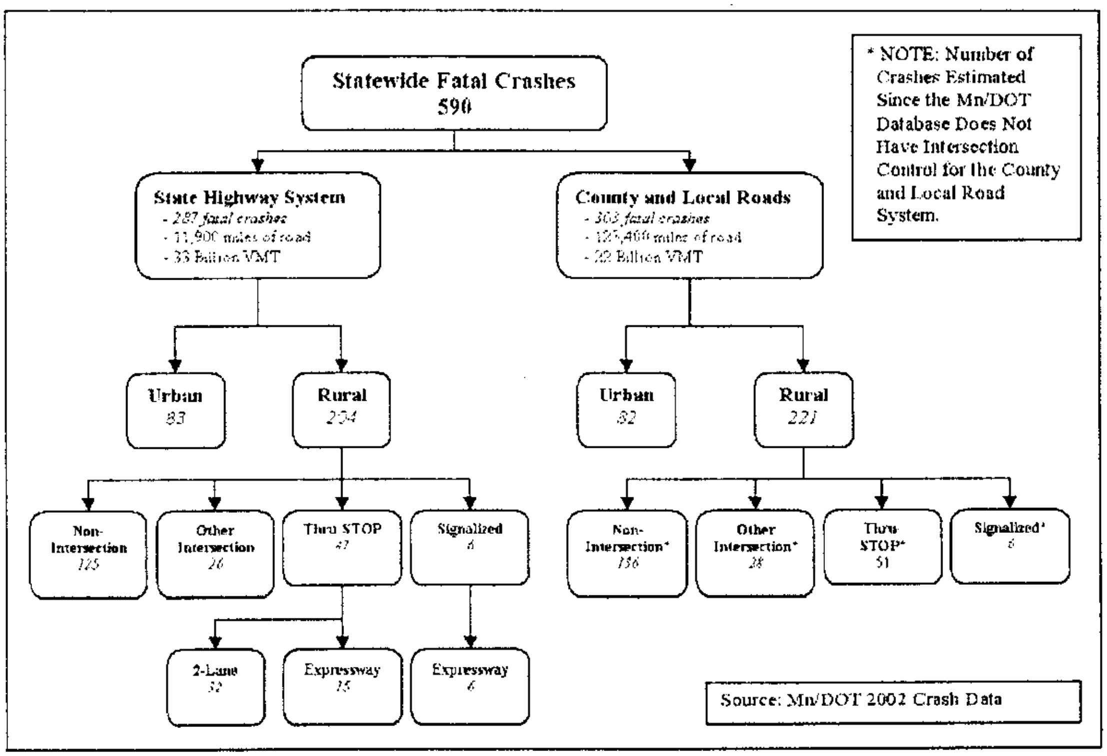

Figure 1. Minnesota crash breakdown using 2002 data[7]

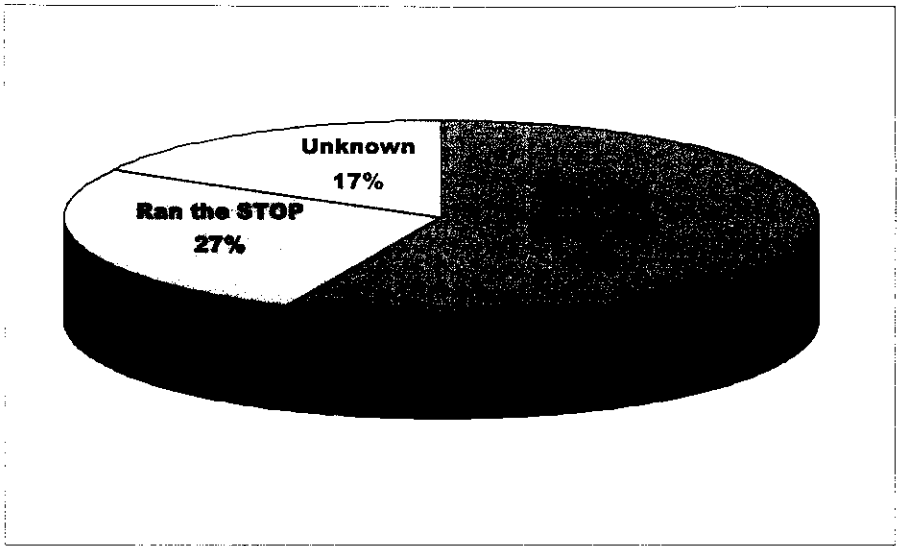

Figure 2. Contributing Factor for Right Angle Crashes at Rural 2-Lane Roadway, Thru-STOP Intersections

Crash Analysis Conclusion. Although the vast majority of crashes occur in urban areas (where urban is defined as a population center of greater than 5,000 population), more than two-thirds of fatal crashes occur in rural areas. The decision as to where to focus VII efforts depends on whether crashes or fatalities are a priority, because this decision has a significant impact on the deployment strategy for VII.

Nearly 75% of all fatal crashes in Minnesota can be described as either intersection crashes or lane departure crashes. Mn/DOT and the University have focused on these two problem areas for the past 4 years. This analysis indicates that this work has been properly focused, and to make a significant impact, work should continue in this direction. Technologies which would enable the deployment of systems to mitigate the rural crash fatality problem have been developed; the open question is how to best deploy them to achieve the highest benefit for the least cost.

The dichotomy between urban and rural intersections for Minnesota is also reflected in crash statistics in other states. Figure 3 and Figure 4 below compare urban vs. fatal crashes for all states in the union. When ranking all states by their rural fatality rate (Figure 3), Minnesota ranks 36th in the country (where the top rank is associated with the worst fatality rate). However, this still associated with an unacceptable 1.8 fatalities per 100 Million Vehicle Miles Traveled (MVMT). When examining the ratio of rural to urban fatalities (Figure 4), Minnesota ranks close to the middle for all states – worse than its 36th ranking for rural fatality rate. Using this measure, fully three quarters of the states have a ratio of rural to urban fatalities that is greater than one. With the exception of a few densely populated states[8], rural fatalities far outnumber urban fatalities. What is interesting is that three of the states (i.e., Nevada, Florida and California) which have a ratio of rural to urban fatalities that is less than one, have amongst the worst rural fatality rates in the country.

[7] From Howard Preston, Richard Storm, Max Donath, Craig Shankwitz, "Review of Minnesota's Rural Intersection Crashes: Methodology for Identifying Intersections for Intersection Decision Support (IDS)," Minnesota DOT Report No. 2004-34, 2004. (available at http://www.its.umn.edu/research/applications/ids/consortium/publications/index.html)

[8] Notably CA, FL, NY, NJ, IL, MD, MA, RI and CT.

Furthermore, if one were to look at causal factors associated with road fatalities (see Figure 5), it is quite clear why fatalities are more likely associated with rural driving. Failure to Keep in Proper Lane or Run-off-the-road is the number one most significant factor in leading to rural road fatalities while excessive speed is number two (by almost a factor of 2:1). Assisting drivers with lane keeping (by providing in-vehicle lane departure warnings) should clearly be our number one priority if our objective is to reduce fatalities.

Before a deployment strategy can be developed, the issues involved with these VII technologies as applied in rural or urban areas should be discussed. Of the six components in the Minnesota VII toolbox listed earlier, only the communication and sensor tools are significantly affected by rural or urban applications. These are discussed below.

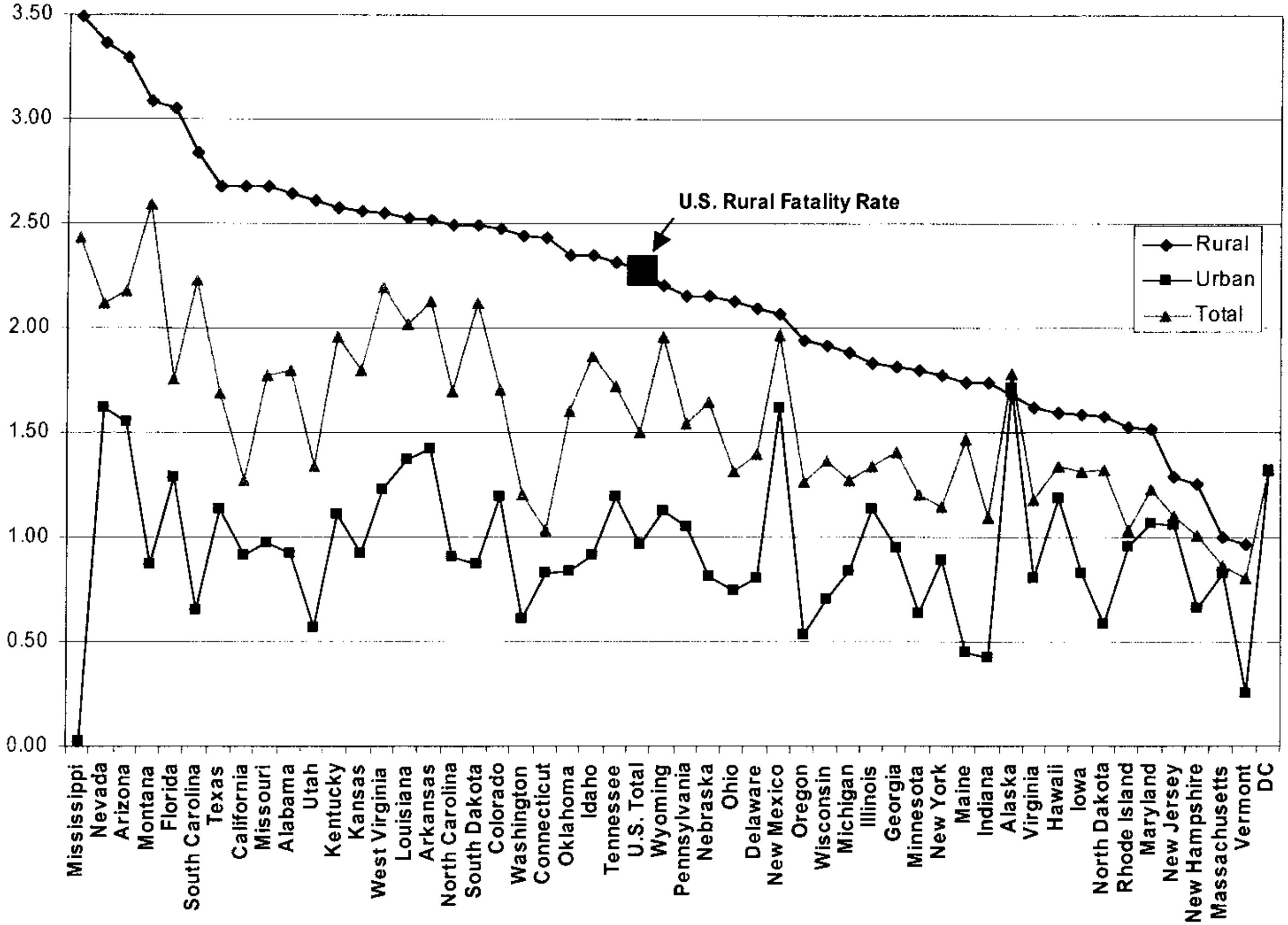

Figure 3. Urban and Rural crash fatalities per 100 MVMT for the United States, based on 2002 FARS data.

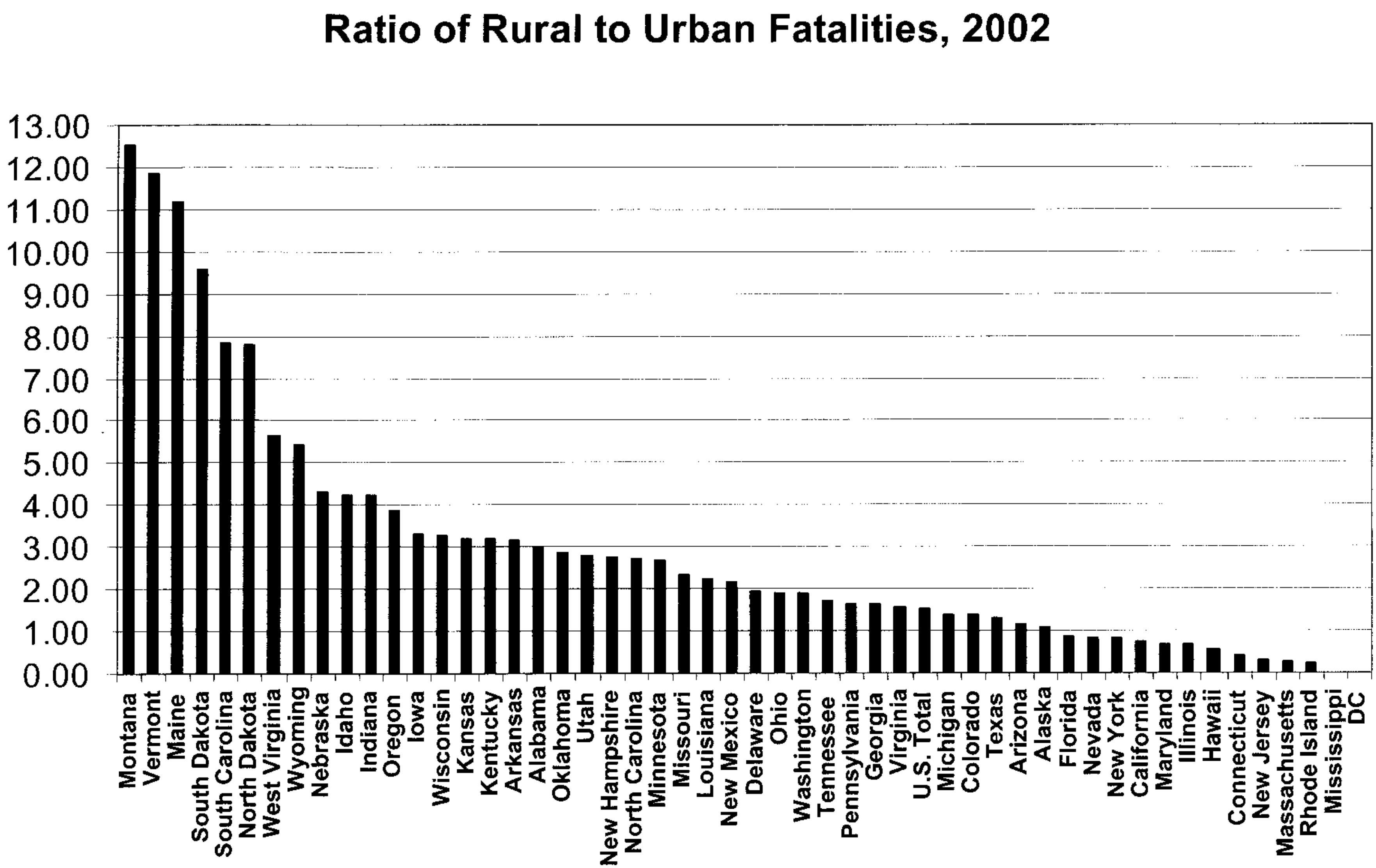

Figure 4. Ratio of Rural to Urban Fatalities for the United States, based on 2002 FARS data.

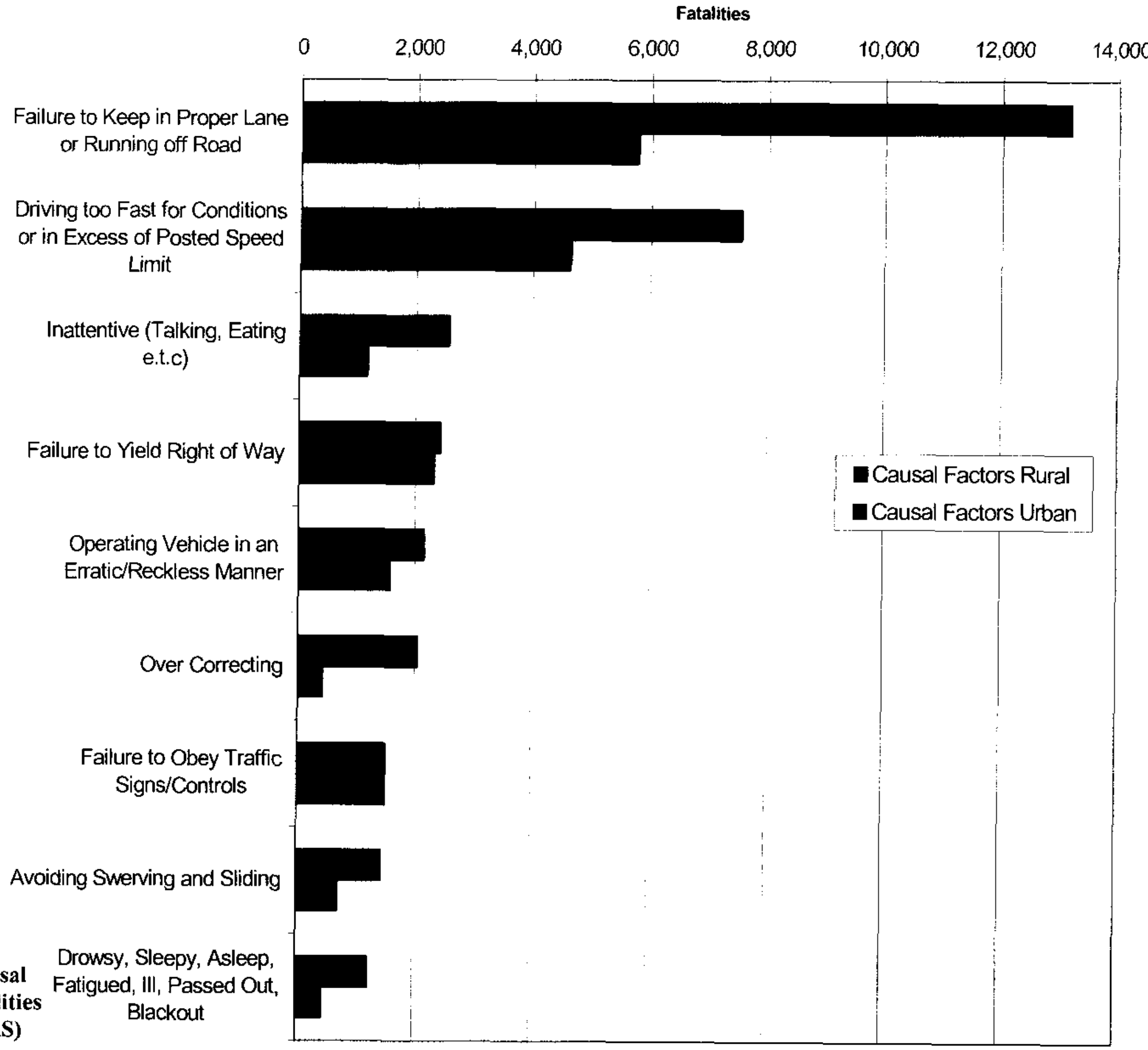

Figure 5 - Causal Factors Associated with Road Fatalities - Rural vs. Urban (2002 FARS)

Urban vs. Rural for the Minnesota VII Toolbox.

The success of any VII project is directly dependent upon the performance of the communication system upon which the system is based. Just as crash statistics are quite disparate for Rural and Urban areas, the issues with communications and sensors (primarily DGPS) systems for rural and urban areas are divergent as well. These are addressed below.

Rural vs. Urban for communication systems: a view of the DSRC model.

The primary issues regarding communication systems for VII applications in rural and urban areas involve bandwidth, range, and deployment cost. All three are related, and a change in any one parameter typically affects the other two. Because DSRC appears to be the communication mode most associated with VII, it will be used as the basis for this analysis.

Bandwidth. In rural areas, bandwidth and the availability of open channels which can be used for reliable, robust communication between vehicles and the infrastructure pose tractable problems. If the DSRC model is used to represent a typical communication mode, 10 channels spanning 75 MHz are available over a range of 300 meters. Assuming moving traffic with an average 20' vehicle length with a three-car length spacing and a 4 lane road intersecting another 4 lane road, the greatest number of vehicles likely to be within 300 meters of a roadside unit is 196. Assuming a 75MHz wide spectrum, 80% channel efficiency, and the roadside unit acting as a router, the local system can support, on average, a 305 kbit/s communication link with each vehicle. This should be sufficient for most safety applications.

In an urban area, bandwidth is more severely constrained. In an area such as Los Angeles, it is not uncommon to find huge traffic jams on wide roads on multiple horizontal planes. Using an assumption of 8 road legs, 4 lanes wide, each supporting traffic in two directions and an average vehicle length of 20 feet places 3200 cars within 300 meters of the roadside unit. Assuming a 75MHz wide spectrum, 80% channel efficiency, and the roadside unit acting as a router, this local system could support, on average, a communication rate of 19.2kbit/s to each vehicle, or roughly 6% of what is available in a rural area.

In this situation, DSRC could support non-safety critical applications which place much lower demands on bandwidth. Electronic tolling applications such as those proposed for HOT and FAST lanes, for instance, impose relatively small demands on a wireless communication link. Investments in roadside units (and in-vehicle transceivers) could be leveraged across many applications, thereby creating a more rapid deployment path.

The utility of DSRC as a safety critical communication device under these conditions requires further analysis based on a specific application.

Signal propagation – RSU Spacing. In rural areas, because of the relatively low vehicle density, a short range communication capability is much less appealing than a system with longer range. Using the DSRC model, with a 300 meter maximum range, complete coverage of the roadway would require a roadside unit every 0.4 miles[9]. To provide coverage of the Trunk Highway system with a gap of no more than 5 seconds at legal speeds would require 23,600 roadside units. County State Aid highways would add another 97,300 road side units. It is highly unlikely that Minnesota (or any state for that matter) would be ready to support nearly 121,000 roadside units on its Trunk and CSAH highway system.

This vast number of roadside units basically points to the fact that DSRC can't be used as a general purpose communication pathway for rural safety applications. It may have

[9] Complete coverage is needed for a DGPS-based lane departure warning system. For robustness, high accuracy DGPS systems require a periodic correction signal. The typical broadcast rate for a CMR correction message is 1 Hz. If the correction signal is more than 5 seconds old, the receiver loses its ability to provide an accurate solution. Complete coverage using DSRC would only occur at a spacing of approximately 2000 feet. Allowing a 5 second gap at legal highway speeds would allow spacing to be at 2400 feet, or 20% greater than complete coverage.

general purpose use for providing information at hotspots (speed limit transitions, sharp curves, intersection collision warning), but for a lane departure warning system where continuous access to DGPS corrections is necessary, it is a poor choice. Alternatives must be found.

In urban areas, limited signal propagation is an attractive feature. By limiting the maximum range of the roadside unit, the number of vehicles able to reliably communicate with the RSU is physically limited. Limiting the number of connections to the RSU implicitly provides a relatively high lower limit on the available bandwidth to each of the communicating vehicles.

Rural vs. Urban GPS/DGPS systems.

As the primary sensor for VII systems, GPS/DGPS systems must also be considered in both rural and urban settings. Because GPS is really a communication system, many of the deployment issues are affected by its ability to communicate with both the satellite constellation and a correction reference station.

The discussion below focuses on high performance, high accuracy (errors 5-20 cm) DGPS, which is needed to provide a lane departure warning system which produces few false alarms[10]. Lower accuracy GPS/DGPS systems providing accuracies of 1 – 15 meters typically work equally well in rural or urban areas; the primary difference is the accuracy of the solution, where receivers in rural areas with clear views of the satellite constellation are likely to get better accuracies than receivers in urban areas, where multipath effects and reduced number of visible satellites tend to increase position errors to the 10 to 15 meter range.

Rural areas. In most rural areas, the source of the DGPS correction represents the greatest impediment to access to high accuracy position data. Correction source issues can be broken down further to location of base station receivers, and the provision of the correction signal to the rover which requires it.

In Minnesota, a number of base stations which support high accuracy DGPS have been located throughout the state, and have been used for a variety of purposes. Mn/DOT, in particular, has been very aggressive in establishing a network of GPS base stations. Figure 6 below shows the location of all DGPS base stations in the Mn/DOT DGPS base station network.

[10] For a warning to be effective, it has to be issued *before* the vehicle crosses the lane. Therefore, vehicle speed and heading must be incorporated with present position into the lane departure warning algorithm so an accurate *prediction* can be made. Without sufficient accuracy, the ability to detect a true lane departure event is greatly reduced, which leads to both false and missed warnings.

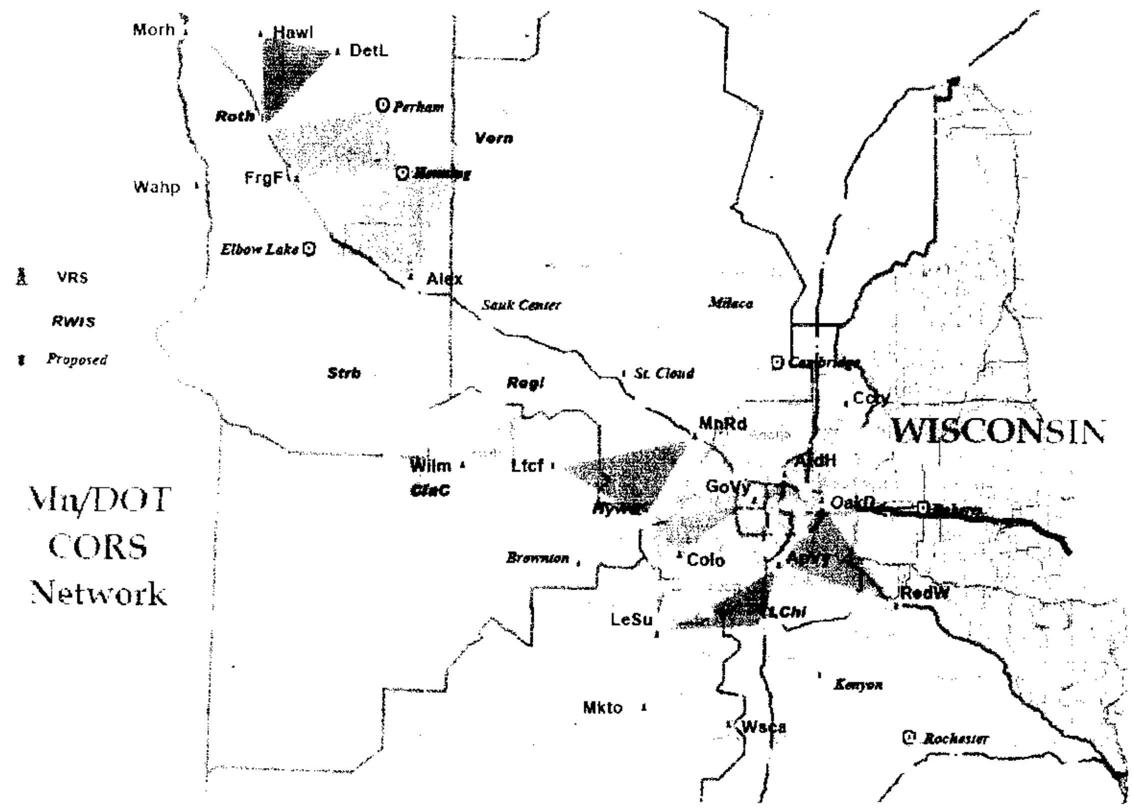

Figure 6. Locations of VRS base stations throughout Minnesota as of 24 June 2004.

This array of DGPS Continuously Operating Reference Stations (CORS) is connected to three servers which run the Trimble Virtual Reference Station (VRS) software. These are used to provide a DGPS correction for any moving vehicle within in the shaded areas. By late summer 2004, with the planned installation of stations at Sauk Centre and St. Cloud, there will be continuous coverage along the entire 260 mile length of I-94 in Minnesota, from Hudson, WI to Fargo, ND. Mn/DOT has plans to provide coverage throughout the entire state, but the funding has been delayed. Don Seitz with Mn/DOT's Geodetics Office estimates that the State of Minnesota could have complete high accuracy DGPS coverage for approximately $2M.

Quoting Don Seitz, "Presently, Mn/DOT uses a combination of RF Modems operating on the public safety frequency band (450 MHz), CDPD modems, and cell phones to broadcast corrections to the rovers in the field. The high speed data phones seem to have the most promise although their coverage can be somewhat limited. In addition we have recently installed an access server which allows communications with more traditional type cell phones which has allowed corrections to be delivered in areas where an Internet connection is not possible at this time."

Other alternatives for providing real time GPS corrections exist. In Polk County, in northwestern Minnesota, corrections from private satellite sources are being evaluated. Yet another alternative is being developed by the FHWA, which is pursuing the enhancement of the Nationwide Differential GPS Service (NDGPS) to obtain real-time decimeter accuracies using the existing NDGPS network of base stations transmitting in the 300KHz band (the HA-NDGPS Program).

Clearly, for lane departure prevention systems, a ubiquitous means to broadcast corrections throughout the state and across the country is required.

Urban areas. As opposed to rural areas where DGPS correction provision is the difficult aspect of high accuracy solutions, the clean reception of satellite constellation signals poses the greatest problem in urban applications. In urban (and suburban) areas, buildings higher than 4 or 5 stories can block the view of satellites and cause multipath reflections which severely limit the ability of a DGPS receiver to attain reliable, consistent high accuracy solutions. For surveying applications, allowing a receiver to have sufficient time to compute an accurate position estimate is acceptable; waiting adds to the cost of the survey, but allows a survey to be complete. For a moving vehicle in a safety application, time is at a premium; "waiting" is a luxury that no one can afford.

High Accuracy Lane Level Digital Maps and Wireless communications.

The implementation of an in-vehicle lane departure warning, such as the one described above, also requires a ubiquitous high accuracy geospatial database, or what in simpler parlance might be called a lane level digital map. Warnings to the driver that take into account the time-to-lane-crossing must know where the lane markings are. Furthermore, they must know where the shoulders and the fog line are located. This implies that the on-board driver assistive system must compute in real time the vehicle's location and heading relative to its position within the lane.

In this scenario, the infrastructure is no longer simply a road-side unit with an accompanying wireless transmission system that communicates with the vehicle; it must also incorporate what one can call the 'soft' infrastructure, the data regarding the infrastructure that is commonly the purview of the state DOT's, counties, cities, etc.

The data contained in a geospatial database must necessarily include the accurate locations of lane boundaries, shoulders, fog lines, and turn lanes. It should also include the location of the adjacent road furniture, including J-barriers, guardrails, medians, traffic islands, etc.. Moreover, relevant attributes including local speed limits should also be included in a proper geospatial database. For example, knowledge about the existence of a shoulder or bridge abutment may dictate the crash avoidance strategy that is used. The local speed limit set by a particular jurisdiction will affect when in-vehicle speed warnings are activated. Intersection warning systems must account for the median, protected lanes, etc.

This geospatial database (much more than a map) cannot be generated simply by aggregating the GPS 'tracks' from passenger cars, as suggested by some. Attribute and accuracy requirements are significantly greater than the centerline information which could be acquired by aggregating 'track'. A dedicated effort is required to develop usable databases.

State and county DOT's are well positioned to develop usable databases, using either lane striping equipment (by digitally recording the location of the nozzles as they spray the lane markings), and/or by using digital image processing techniques which determine and record the global position of lane stripes as DOT maintenance vehicles pass over or nearby them. Digital data collection can be done in real time, with subsequent data compression and processing performed in near real time. Data collected in the morning can be compressed, processed, and validated in the afternoon.

In our projections, digitizing the rural roads themselves will cost on the order of $150 per mile. Given approximately 3 million miles of rural roads in the US, the cost of such an endeavor is not out of the question. $450 million for digitizing all of our rural roads at the accuracy required for lane departure warning systems is a "drop in the bucket" when one considers the costs associated with "hard" transportation infrastructure. (To put this number in perspective, a new Twin Cities 12 mile Light Rail Transit system is expected to cost $675 million.) The benefits of improving the safety of our traveling public is significant, but there are also benefits that will directly accrue to the states. For example, such a "map" would improve the efficiency of lane markings application, would enhance asset management systems, and would provide enhanced georeferencing.

With that introduction, how does wireless fit in? Our model assumes that an up-to-date high accuracy digital map is provided by each state to the driver annually (when updating the license tabs) and is then loaded by the driver into the vehicle's On-Board Unit (OBU). However, as we all know, the roads do change; road construction is a continuous process. To ensure map accuracy, any changes to the configuration of a road should be broadcast wirelessly from an RSU both during construction and for a mandated, fixed amount of time after the construction is complete. This would ensure a driver relying on an assistive system will have the most accurate data available. Such a scenario would require an RSU architecture that would be somewhat different than that proposed to date. Additionally, it may be possible to consider DSRC as the mechanism to provide such wireless updates. However, addressing these questions is beyond the scope of this document.

VII Directions and where Minnesota should move.

The path Minnesota takes with VII should be based on where Minnesota sees the greatest need for improvements in the transportation network. If Safer, Smarter, and More Efficient are the critical areas, with safety the greatest priority, then the following make the most sense.

A. First, focus on rural fatal crashes. On a national basis, sixty-one percent of traffic fatalities occur on rural roads. In Minnesota, two thirds of the fatal crashes occur on rural roads. Of these fatalities, 76% of these fatalities can be classified as either lane departure (54%) or intersection (22%). To achieve measurable results in the least amount of time, effort should be focused in this area.

Traditional approaches to safety improvements have reached their limits. This is indicated by the fact that in Minnesota, traffic fatalities have reached a plateau. Figure 7 below provides a historical look at traffic fatalities in Minnesota over the past 42 years. Improvements in vehicle crash worthiness, air bags, ABS, and a greater awareness of the repercussions of drunk driving lead to the "flattening" of the curve. For a significant decrease in highway fatalities to occur, a new paradigm is needed.

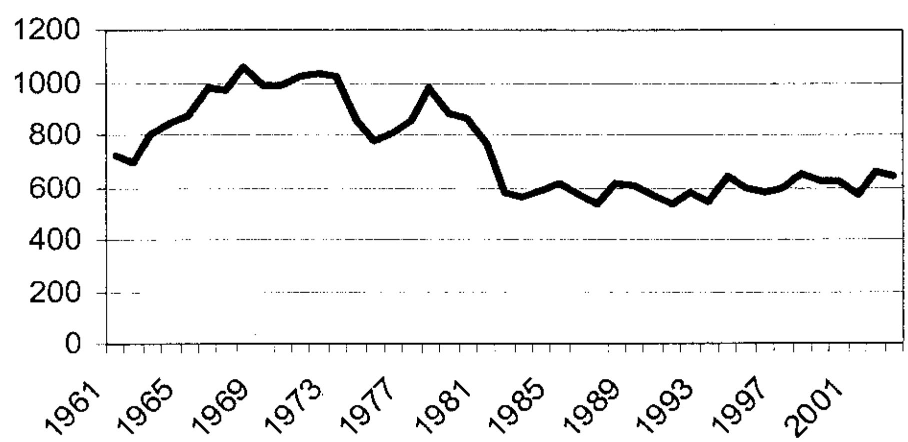

Figure 7. Minnesota Traffic Fatalities, 1961-2003.

Reduce lane departure crashes. A number of approaches to lane departure crashes have been developed over the past 2 decades. Approaches include vision based systems, magnetic tape/magnetic plug based systems, and DGPS based systems.

Vision based systems are undesirable in northern climates where lane boundary markings are often obscured by blowing or drifting snow, covered by fallen snow, or worn out by abrasion with snowplow blades. Lack of robustness makes their deployment difficult.

Non-vision based lane departure warning technology has been developed, tested, and analyzed in Minnesota since the mid-1990's. Two separate technologies have been tested by Mn/DOT: the 3M Lane Awareness System, and the University of Minnesota DGPS system. Both systems relied upon Vehicle Infrastructure Integration. The 3M system used a magnetically coded tape either embedded or inlayed in the pavement to provide a local magnetic field reference. A sensor mounted on the vehicle measured the local magnetic field strength across an array of magnetometers. Based on both the absolute field strength and the relative strength along the sensor bar, the distance from the tape to the sensor could be computed with an accuracy of approximately 5 centimeters. This system was installed and field tested on a number of snowplows in Minnesota from 1998 – 2002 [This tape system is no longer manufactured by 3M].

The second lane departure system uses accurate DGPS (5 cm errors) and high accuracy geospatial databases to compare vehicle position with road position. If an imminent lane departure is sensed, timely warnings are issued to a driver. This system is presently installed on 5 Minnesota snowplows, 2 Alaska snowplows, a state patrol car, and a transit bus.

In the event that a driver does not respond at all, a system has been demonstrated which can take control from a driver and bring the vehicle to a safe stop on the adjacent shoulder.

This technology has been proven, but deployment has been delayed for two reasons. First, the dual frequency, carrier phase DGPS receiver upon which the system is built is quite expensive at $12,500 per unit. However, the worldwide market for this system has been quoted at 5000 units. Discussions with a DGPS manufacturer has indicated that in volumes of 1 million per year (one on every 14 cars sold in the US per year), OEM cost for the necessary hardware would be on the order of $100. Given these volumes and the economies of scale associated with electronic manufacturing, this $100 estimate is credible.

The greater impediment to deployment, however, is the present lack of a ubiquitous means with which to broadcast DGPS corrections over the entire state (and extrapolating, over the entire US). Unlike the problems faced by a manufacturer of electronic devices (who has control over the manufacturing process), deployment of the means to broadcast these corrections falls under the auspices of the FCC.

An alternative to the local correction broadcast problem has also been explored. Satellite based correction services can provide corrections enabling a position solution accuracy of approximately 15 cm. However, systems relying upon satellite based corrections are significantly less robust to multipath effects, and require significantly longer times to recover from a loss of satellite or correction signal. With further development, it is likely that system performance may improve enough to avoid the need for ground based corrections, at least in rural areas.

The remaining components of a DGPS-based lane departure system, including the digital maps, algorithms, and human-machine interfaces have been worked out.

Actions:

1. With the deployment of the Minnesota VRS system, the primary technical impediment to deployment of a ubiquitous lane departure system is the provision of DGPS correction signals. The system used for DGPS corrections could also support a statewide E-911 communication channel. (Rural E-911 calls are infrequent compared to the repetition rate for DGPS correction broadcast).

   Initial work with the Mn/DOT Office of Electronic Communications to investigate the potential of a statewide frequency allocation and correction broadcast scheme for high accuracy DGPS would open the door for a ubiquitous, all weather lane departure system which would be effective throughout the US. Positive results here will greatly expedite the deployment of lane departure warning systems.

2. In parallel, a further examination of performance and other issues associated with satellite based DGPS corrections should be undertaken. Presently, satellite based corrections are used in a snowplow driver assistive system in Polk County, MN. The unit performs well when the system maintains both GPS and correction satellite lock, but is slow to recover if lock is lost (1 to 2 minutes to recover as opposed to 7-15 seconds with local corrections.)

3. With results from 1 and 2, a decision to pursue a local (i.e., statewide) approach to the provision of DGPS correction signals should be made. If the decision is positive, a small network should be constructed and tested as a means to evaluate the system. Positive results would motivate a field operational test.

4. Conduct benefit: cost study for deployment using the methods described as part of the TZD initiative, for comparison. The TZD initiative lists a number of solutions as a means to reduce traffic fatalities in the State of Minnesota. TZD methods range from improving lighting to upgrading 2 lane rural roads to 4 lane rural roads. These costs should be used as a basis to judge VII safety applications for rural areas.

5. Using the corridors already covered by DGPS correction signals, conduct a field operational test to evaluate high accuracy digital map architecture prototypes for lane departure warning, methods for using DOT fleet vehicles to rapidly develop such high accuracy maps, and means (i.e. VII and local

RSU's) for wirelessly patching to accommodate shifting work zones. A workable high accuracy digital map and VII RSU architecture must allow for map update transmissions to vehicles to accommodate road construction or other maintenance operations. Such wireless transmission can be provided from either fixed RSUs, or from units mounted on fleet trucks that move with the shifting worksite.

Reduce rural intersection fatalities. Minnesota is a full partner in the FHWA's Infrastructure Consortium, and is developing an Intersection Decision Support (IDS) system. This system, initially designed to improve the safety of drivers attempting to cross or enter the traffic stream on high speed rural road, provides the driver with vehicle-specific information describing when it is unsafe to enter the intersection. Roadside sensors along the high speed legs determine the speed and location of all vehicles on these legs; this information is passed to a central processor which determines the "state" of the intersection as well as the location, speed, and size of all gaps in the traffic at the intersection, and passes this information to the driver via a roadside mounted driver-infrastructure interface (DII). Based on Minnesota crash statistics, this system would address the conditions that lead to approximately 56% of rural intersection crashes.

To reach the greatest number of users in the least amount of time, the IDS project uses a DII to convey information to the driver. Two logical applications of VII, and DSRC in particular, are likely to enhance the performance of this system. First, DSRC could be used to transmit warning information directly to the vehicle on the minor road, enabling a vehicle-driver interface to provide the necessary cues to the driver. Second, driver-vehicle information (i.e, driver age, acceleration habits, records of previous trajectories at a particular intersection, vehicle type, etc.) stored on-board the vehicle could be passed to the intersection controller as a means to tailor the warning to the driver's habits and likely behavior. Custom warnings offer higher performance and increase the chance of driver acceptance of the system.

In addition to poor gap selection, 27% (or half as many as bad gap selection crashes) of rural Thru-STOP intersection crashes have "running" the stop sign as a causal factor. In Virginia, VDOT and VTTI are developing a system to do both infrastructure based warnings and in-vehicle warnings. The Virginia team is using roadside sensors to determine the likelihood that a vehicle will run a stop sign or stop light. When the probability is sufficiently high, a warning to stop is issued to the offending driver. Indications by the Virginia team indicate that in-vehicle warnings offer, in this use case, a greater chance for success because the driver does not have to focus attention on a particular sign to receive a warning.

In Minnesota, developments aimed at the deployment of a lane departure system could be used to prevent red light/stop sign running. The algorithms developed by Virginia can be incorporated into a DGPS – digital map system, thereby allowing lane departure and stop sign running to operate using the same computational platform. The in-vehicle system can sense that a driver is approaching a stop sign (whose location is known from the on-board digital map) in a manner indicating whether he/she is unlikely to stop; a vehicle based warning can then be provided to the driver in sufficient time to elicit a stop. Such a technique would eliminate the need to instrument each intersection with sensors and a driver interface to provide warnings, and would leverage resources already in place for DGPS based lane departure warnings. This may help in reducing rear end crashes occurring at rural signalized intersections.

Actions:

1. Monitor the progress of the Virginia intersection red light/stop sign running program, and consider its evaluation as part of a field operational test of IDS technologies.

2. Conduct a crash analysis to determine a candidate intersection where such a system (and supporting DSRC) can be evaluated.

B. Second, focus on urban traffic flow and crash mitigation. Clearly, urban areas suffer from the greatest concentration of crashes, and as such may be another attractive target to consider. The decision as to which priority to consider is a policy and budgetary decision beyond the scope of this document. However, more analysis is needed to determine whether urban intersection crashes or urban freeway crashes place a higher toll on society in terms of lost time, congestion, and environmental concerns. Urban applications best suit DSRC as a communication platform for VII.

Actions:

1. **Determine urban crash characteristics.** The statistics show that for rural fatalities, addressing lane departure and intersection crashes will address 76% of the rural fatalities in Minnesota. For urban crashes, the numbers are not so clear. Whether lane departures, rear-enders (primarily on congested freeways), or intersection collisions warrant the majority of resources will depend on the results of crash analyses.

2. **Conduct further analysis of DSRC as an urban communication platform.** As has been pointed out earlier, DSRC is well suited to urban areas where spot coverage over a small range (300 meters), high bandwidth, and a relatively low number of maximum connections appear to make it a favorable choice for urban safety applications, including passing traffic probe data, intersection collision warnings, and electronic tolling applications. The problem, however, is that no hardware presently exists which can be used for evaluation.

   Unknowns associated with DSRC include cross talk, channel allocation, safety prioritization, noise sensitivity, etc. Before a commitment to DSRC (and the technologies it may be asked to support) is made, a more comprehensive test program is needed. Minnesota should act as a beta test site for emerging DSRC hardware. Once performance characteristics are better known (and modeled), strategies for its use can be formulated.

3. **Identify a comprehensive strategy for VII.** Once action 1 above is complete, a more comprehensive picture of the urban crash problem will emerge. Strategies will range from the simple to the complex. For instance, if intersection crashes (rather than fatalities) represent a priority, then specific approaches ought to be considered. For example, if sign or signal violation is found to be the prevailing problem, then solutions to this problem, presently under development in Virginia, may be appropriate. That technology could be applied in Minnesota (or anywhere in the US).